Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 118 (2015) 958 – 968

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

Co-benefits of energy and buildings data: The case for supporting data access to achieve a sustainable built environment

Ian Hamilton[a], Tadj Oreszczyn[a], Alex Summerfield[a], Phil Steadman[a], Simon Elam[a] Andrew Smith[a]*

UCL Energy Institute, University College London, 14 Upper Woburn Place, London, WC1H 0NN

Abstract

Supporting the development of a strong evidence base on which to improve the energy performance of buildings requires having access to research from different 'levels' of data. This includes high-level studies to carefully constructed representative samples, exploratory and investigative studies. As sensors and data collection becomes more widely applied within buildings (and the broader built environment) a clear articulation of the potential benefits and risks of data access is needed to avoid unintended consequences and regressive positions to data access.

The objective of this work is to identify and discuss the co-benefits of energy and built environment data and the mechanisms needed to enable them. We outline a number of potential benefits and limitations of making energy and buildings data more widely available.

Access to and linking/ matching together data can provide numerous benefits, including: research benefits, education and training, academic benefits, funder benefits, policy benefits, among others. However, there are also concerns of making data accessible including: privacy, management of access and communication protocols, commercial sensitivity, intellectual property, and archiving and legacy repository. The mechanisms needed to support data access should include requirements from funders for long-term data management and sharing, funding available for data archaeology, journal requirements for publication, government support and evaluation requests, and industry interest in capturing wider benefits from proprietary data.

Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015

* Corresponding author. Tel.: +44-203-108-5982.
E-mail address: i.hamilton@ucl.ac.uk

1877-7058
Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015
doi:10.1016/j.proeng.2015.08.537

Keywords: Energy, Buildings, Data, Co-benefits

1. Introduction

Policy that aims to manage and shift energy demand and use in buildings requires an evidence base to inform the shaping of instruments and mechanisms to achieve desired outcomes. The ultimate goal of achieving a sustainable built environment in terms of energy demand in buildings requires information on the many interacting drivers that extends beyond the envelop of a building.

Essential to the development of a strong evidence base is the use of empirically derived data from large populations that can represent the real-world conditions of a complex building stock and population. Evaluating policies and determining the effect of technologies *in situ* in millions of buildings means using techniques that support that level of analysis.

However, for the most part, basic information about energy demand in buildings, e.g. trends and patterns along with simple descriptions of population and stock segmentations is limited or simply lacking [1,2]. Without even basic descriptions and agreed metrics of energy demand in buildings, developing a policy framework to achieve change in demand is undermined by the general lack of a robust evidence base and a misunderstanding of consequential drivers. Historically, this lack of evidence is related to prioritization of funding and study, the transient nature of academic research, and a dearth of observed data and therefore reliance on models that are often poorly informed or outdated [1–3].

A number of experts have called for a strong foundation of evidence-based policies and strategies to achieve targets for energy demand, climate change, and other socio-economic goals [1–7]. These same authors outline that the robust evidence must be made up of the latest best-practice information drawn from relevant research that is properly designed, conducted, interpreted and presented; and drawn from inter-disciplinary activities that address the complex, contextually distinct and politically diverse nature of energy demand.

Supporting the development of a strong evidence base on the energy performance of buildings requires having access to research from different 'levels' of data, from high-level aggregate ecological style studies (i.e. using small area statistics), cross-sectional studies of individual units of observations (people, buildings, households, premises, meters, etc.), carefully constructed representative samples, exploratory and investigative studies (which in turn need to be examined within the population again.

The energy and buildings field faces a major challenge in being able to draw together insights from existing conditions and applied technologies due to the absence of or limited access to high-quality people and buildings data and high-resolution energy data. Further, although significant sums of money have been spent on data collection in field trials and research programmes, there is limited capacity and resources allocated to organising and archiving the data. To ensure that research data has a life beyond the project, it is essential that the data is stored and that it contains sufficiently detailed meta-data in order to be used by other researchers. Data must also be logged and made available to the wider community from accessible repositories; for example, the UK Data Archive. The risk is that without detailed data collection and storage, longitudinal analysis or systematic reviews of research findings is not viable to support project-by-project learning. The implication of this limited data collection and access is that empirical studies have had a limited impact on the policy process.

Therefore, without better data and more joined-up interdisciplinary research we risk being able to identify and mitigate the unintended consequences of our actions in the transition towards a sustainable built environment for energy demand and buildings. The objective of this work is to discuss the co-benefits of data in transitioning to a sustainable built environment for energy demand and buildings and the mechanisms needed to enable them.

2. The current situation

Though ambitious plans and policies are being developed to tackle the climate change and energy challenges, research on energy demand in buildings has been criticised for being largely incapable of describing even the most basic conditions around energy demand [5]. For example, in examining the estimate for mitigation potential in buildings from the IPCC, Oreszczyzn & Lowe say:

> "[The estimate] prompts a number of concerns. The most important of these is the poor quality of the data available to support the [estimate]. This concern in turn stems from weak links between the policy research community responsible for producing the [estimate], the building science research community responsible for producing the underlying data and analysis, and the communities of practice responsible for translating the speculations presented above into reality."

They go on to discuss the implication that this paucity of data means for addressing energy demand in dwellings, seen as 'low-hanging fruit' by policymakers, but which is vastly more complex and difficult than imagined. They challenge policy orthodoxy that states that interventions in the building stock aimed at reducing energy demand are 'quick wins' and cost-effective.

The simplistic approach to the understanding of energy demand and the built environment is a key risk for why policies may not deliver expected outcomes, e.g. energy demand reduction, carbon savings, etc. For example, despite many programmes and policies targeting the UK's energy use in the housing stock, changes in real energy demand have been limited and generally poorly explained [1]. Summerfield and Lowe (2012) point out how the lack of good quality information on energy use, buildings and technology and households and their practices severely limit researchers and governments ability to address the decarbonisation challenge across a heterogeneous and complex building stock and its occupants. They go on to set out the challenges for achieving the transition to a low carbon society which include: the scale of emission reductions needed, the rate of change needed in emissions and transformation to the energy system, the scope of the sectors and actors interacting in the built environment, and finally the trans-disciplinary approach needed. One of the key features of their approach to addressing these challenges is the role of empirical evidence and high quality data.

At present, however, much of the research is either too focused on small samples or single cases or is hindered by lack of funding for large empirically-driven survey or monitoring projects [1,7]. The dearth of funding in energy demand forced a lot of research activities away from empirical data collection and analyses towards theoretical research, this latter approach being facilitated by the availability of cheap computing power [5].

Empirical collection of data on building characteristics and energy demand has therefore been ad-hoc or subject to interruptions and there has been little tradition of reporting data in a formal sense, thus undermining any concerted advances in the research [1]. When data is collected on an ad-hoc basis it very often lacks key features that allow for cross-comparison or linking to a broader foundation and therefore risks misunderstanding and limited evaluation. The overall effect of this lack of data collection has meant that models that attempt to describe energy demand in buildings have been seriously limited and often rely on unconfirmed theory rather than empirical observations.

The study of energy demand in buildings is now at a point where the importance of data needs to be more clearly recognized and along with this the development of processes for handling data collection, storage, access and distribution. With the emergence of interval meter data, ubiquitous sensors and large data frameworks of people, energy and buildings data, recognized processes for handling data will help to structure existing research practices and help guide interdisciplinary research.

An important factor coming to bear on the energy and buildings research and design field is ‘Big Data’. The concept of ‘Big Data’ is emerging within the energy and building sector and is loosely being applied to other terms such as ‘smart’ devices (e.g. meters, sensors, appliances) that have the ability to create data logs, such as a range of sensory inputs (e.g. temperature, humidity, presence detectors) or resource flows (e.g. electrical power demand) or other devices. While computer and information scientists may conceptualise Big Data in terms of the total storage size of data, this doesn’t necessarily capture the implication that the growth in data creating devices really have on the field. Boyd & Crawford (2012) make the point that Big Data is a cultural, technological and scholarly phenomena that is drawn from the interaction of technology, analysis and a sense of mythology [8]. The latter point reflecting the tendency for large datasets to be seen as having their own hidden insights and truths that will emerge through their use. Big Data is more likely to be an oracle, providing ambiguous and possible obscure messages as often as it might provide these ‘truths’. As Boyd and Crawford point out, “bigger data is not always better data”. In the energy and buildings field the access and use of big data may provide the stimulation needed to examine long held assumptions on how and where energy is used and, when connected to information about the users, the practices for why it is demanded.

Recognising what Big Data means for the energy and buildings field will ultimately help inform providers and users of this data on its opportunities and limitations. The collection of data through ‘smart’ devices and the drive of researchers to access and use the data in their analysis and for building designers and users to better understand their buildings means that a structure around which data is collected, curated, and shared is vital to ensuring data has the opportunity to be used, and for any available insights to be gained. We must also address the potential concerns that accompany the growth of the collection and use of large datasets in the energy and buildings field. Any data structure that is put in place must recognise the challenges that energy and buildings (and people) data face in terms of privacy, cost and ownership, otherwise the risk to the research and design community is that this emerging field of data will be limited or lost.

We recognise several significant challenges relating to data and energy demand research, these are:

- The lack of access to good quality, high resolution energy data of the statistical quality that most other disciplines would consider a pre-requisite for the pursuit of good science and robust conclusions.
- A limited capacity to analyse, organise or archive data, despite significant sums of money invested to collect data through individual projects.
- No basis for systematic reviews of research findings, and little basis for project-by-project learning, have resulted in limited impact of data on the policy process.
- Poor access to data makes it difficult to establish and maintain benchmarks for performance or to ground models. Practitioners have been left without usable guidelines, and policymakers without the tools to devise and evaluate policy.

In making energy and buildings data more accessible, ensuring that it is of high quality, that it is organised and described in detailed terms, and with a greater pool of available resources to create and analyse data there is the potential to capture a number of benefits that may otherwise not be realised.

3. Co-benefits of data

The potential benefits of high quality, well organised, and accessible energy and buildings data will likely accrue to a number of researchers, practitioners and institutions, extend the impact of research, and result in innovative findings where data is newly available or linked together.

The largest body of literature of the 'benefits' of 'data sharing' have largely come from the health research field, a group that have been pushing the envelop on data sharing for several decades. Data sharing in health research was driven by the need to address pressing health problems, for example to understand the control of chronic disease which have many attributable factors or to better understand underlying physiological and genetic makeup of the population. These activities require (and generate) large amounts of data (particularly in the case of genetic sequencing) that must be accurately described to ensure transparency and consistency, securely stored and accessed to ensure privacy, and made available to a wide number of scientists and practitioners who can work with policymakers to improve overall health. Although improving the energy performance of buildings may not be of the same social priority as addressing health problems, the transition to a low carbon and sustainable infrastructure and working to understand the implication of such a transition on indoor environments may help to avoid potentially negative impacts.

3.1. Benefits for researchers, practitioners and institutions

For research, a number of benefits have been identified within the literature improvements in research and knowledge transfer in the academic sector, including: improvements in research and training, increased recognition of academic research, efficiencies in funding, improvements to societal wellbeing through understanding.

For the purposes of education and training, access to data that is well-structured and of a high quality can help improve data literacy and provide educators with a resource from which to allow for guided learning. In the energy and buildings field, one of the main reasons why data is both difficult to access and poorly structured is because many of those working in the field had little or no formal training with data collection, analysis and data management. By introducing data into the curriculum of engineering and architecture (the dominant professions working on energy and buildings) there will be an improvement in how future practitioners are able to handle the coming torrent of data. It will also prompt educators and researchers into thinking more clearly about what data, its use and control means in terms of ethical considerations and transparency of the science conducted.

The benefits for the research field overall can include getting research results more quickly into the public domain and into practice. Piwowar (2008) outlined that data sharing in health settings led to improvements in best practice performance standards [9]. For energy and buildings sharing data as well as results from field trials, for example, will help practitioners identify problems and implement standards that improve the design, service provided, or technology installed. This would have the effect of accelerating how research findings are applied into the field. Further, if data sharing becomes part of the dissemination processes there is more likely to be opportunity for collaboration between those working on similar topics who can share methods and develop improved analysis techniques.

The availability of large empirical datasets may also help to increase the number of hypothesis-led research studies. Examining data and describing trends and patterns will provide a means for positing hypotheses that can be subject of further studies – and for researchers, further funding if the question is sufficiently novel. It may also be that large datasets generated from project may result in new types of scientific enquiry [10]. For example, in the UK the availability of several formerly unpublished datasets as provided an opportunity to examine energy demand in hundreds of thousands of non-domestic buildings to derived floorspace statistics that had previously been unavailable. This data resource has further expanded into efforts to characterise the million (or so) non-domestic premises and for the first time begin to define the number of non-domestic buildings in the UK and their activities [11,12].

Although wider benefits may be apparent to researchers, it is not necessarily the case that an individual will recognise the benefits of sharing their data. For academics, benefits include increased recognition of research efforts and ultimately to an increase in citations. Piwowar (2007) showed that when health researchers made their data available to the wider research community that their subsequent citation numbers increased as compared to those whose data was not made available [13]. Therefore, shared data increases researcher citation rates, an important benefit for metrics of academic performance and impact of research.

There is also benefits for funders in terms of funding efficiency and the longevity of their investment. When a dataset has a long lifetime and is used by a number of researchers it can add value to what is often a (relatively) expensive undertaking (i.e. the procurement of data).

3.2. Extend the impact of research

Data sharing has benefits for extending the impact of research on energy in buildings in terms of policymaking and evaluation, determining real world impact of design and technologies, and enhancing smaller datasets and studies.

Evaluating past policies and programmes used to address specific energy demand or related issues is essential to developing effective plans that are able to meeting the set objectives. There is real risk that without high quality and representative data, free of (or with limited) bias, policies cannot be informed by past practices. The lack of data and evaluation also makes it harder to identify and understand the causes of unintended consequences or features of policies that did or did not work, and why.

Using established evidence from empirical data in the development of policy can provide help to ensure policies that are evidence-based, informed by the latest findings from laboratory experiments and real-world experience. Developing evidence-based policy is a challenge not least because often policymakers are faced with limited available evidence on the issues that they are faced with. Policy has to address messy reality and with research undertaken with large datasets collected from real world experience, the change of evidence being relevant to policymakers needs is vastly increased. Data may not necessarily result in more evidence-based policy, but it is unlikely that it would limit it either. A recent evaluation of the UK's largest programme to provide energy efficiency retrofits to low-income households and those at risk of being in fuel poverty (known as Warm Front) used a number of empirical datasets collected during the course of the programme (for which reporting and evaluation was built in). The data was used to evaluate the delivery process of the programme and whether it met a number of targets related to costs, household targeting, delivery times, complaints and market stimulation [14]. The programme covered a wide number of actors within the programme including information on the retrofit installers, retrofit suppliers, households and delivery agents, totalling millions of data points. The results of the evaluation provided policymakers with insights that were directly relevant to policies in development.

In the energy and buildings field, large databases and datasets of sensor and meter data are being used for a range of research. For example, large datasets on the UK housing are being use to determine the uptake and impact of energy efficiency retrofits for millions of homes (approximately 16 million houses or two-thirds of the UK housing stock) [15]. In that instance, several large databases on reported retrofits were merged with the annual metered fuel use in the dwelling to determine the potential actual impact of the retrofit on energy demand using data from before and after the intervention. Linking these datasets together provided any opportunity to not only look at a case example of several dozens or hundreds of dwellings, but of large representative samples that could reflect the heterogeneity that is exhibited within the 'real-world'. Others have examined user temperature demand patterns from millions of temperature data-points across hundreds of dwellings in order to determine when heating systems are coming on (and therefore updating outdated model assumptions) [16]. The use of high-resolution electrical meter data to identify appliances from plug-load signatures provides a method of using 'smart' meters to identify 'dumb' devices [17]. In the UK, 'smart' meter energy data for gas and electricity will become a major resource for researchers and developers interested in the built environment. The UK Government is still determining how access to this resource will be organised but they recognise that this data will play an important role in facilitating the transition of the built environment towards a low-carbon and smart economy.

When data is collected on a regular and consistent basis it can enable cross-comparison or provide the means to contextualise smaller bespoke study designs. This would help to address the problem where models have lacked data from which to parameterise conditions allowing for relationships to be drawn from empirical distributions that include ranges of uncertainty (something that is often lacking in energy and building models). For example, more widely available data on the actual use of fuels among the UK dwellings and households would provide a basis to examine trends and differences in energy use based on empirical information and move away from deep decarbonisation pathways that are derived from notional building-physics based models, which are known to be severely limited when describing real-world trends [18]. The clear benefit of having access to large databases of empirical data on energy demand in buildings would be greater certainty in addressing climate change.

3.3. Innovative findings beyond energy and buildings

There is the potential that making energy demand and buildings data more accessible will result in new and innovative findings beyond energy and buildings research.

Several studies in the UK that focused on health impact and energy efficiency in buildings have begun a process of linking together mortality and morbidity (i.e. hospital admissions) data to energy efficiency retrofit data in millions of dwellings (NIHR PHR 11/3005/31). The premise of the study was that linking together these datasets on health and building energy performance will help to determine what effect these retrofits have on health outcomes related to cold-related diseases. Studying 'natural-experiments', which are events where individuals are naturally exposed/unexposed to a risk factor or putative disease-modifier through circumstances outside the control of the researchers, are made possible when large data sources that can be linked together are made available to researchers.

There are wider social and economic benefits that may be accrued with the availability of high-quality energy and buildings data. Users of buildings will gain better insight into the energy performance of their building either directly through accessing their own data or being exposed to those who have. This can empower users to seek improvements in systems or conditions that may ultimately change their quality of life, or improve the value of their building or portfolio. Economic benefits may include providing better information on selection and investment in technologies or purchasing more efficient dwellings, for example.

4. Addressing Barriers to data access

In health research, data is commonly collected with the aim of developing datasets that are comparable while avoiding sources of bias. Data is collected through disease registries for individuals, often in clinical or hospital settings, or new studies using the designs mentioned above. Data used in epidemiology studies that come from aggregated collections (known as 'routine' data) is used to describe multiple individuals within a an area and time period and is often used to study the prevalence and to suggest hypotheses on the basis of which more complex study designs are applied. To be valid, specialized designs are used to identify associations and links between causal factors, and these need to tackle issues of sample population, size, variables, and ethical considerations to name a few. As a result, studies of disease are often subject to high degrees of justification and scrutiny from expert panels prior to research funds being granted. This has had the effect of formalising the data collection approach and instilling rigour in the science. Collecting established data over an extended period provides the opportunity to undertake longitudinal health studies, an important element in tracking changes in disease patterns and evaluating policy. However, even within the health sector data sharing is recognised as being difficult. Piwowar (2008) says:

> "Sharing biomedical research and health care data is important but difficult. Recognising this, many initiatives facilitate, fund, request, or require researchers to share their data [1–5]. These initiatives address the technical aspects of data sharing, but rarely focus on incentives for key stakeholders [6]." (Piwowar, 2008)

These concerns are picked up in Borgman (2012), who outlines the reasons why data is often not accessible.

> "The reasons for not sharing data are many. Researchers may lack the expertise, resources, or incentives to share their data. Data often do not exist in transferable forms. Some data are not sharable for ethical or epistemological reasons. In many cases, it is not clear what are "the data" associated with a research project." [19]

Preserving privacy and anonymity in linking of datasets is very important. Large datasets in particular offer vast benefits for being linked together with other data to support studies that had not been envisioned but that could help extend knowledge in new and novel ways. However, such links must be undertaken with consideration for ethics and with sufficient protocols to ensures privacy is respected. In cases where linking small-scale studies for specific individuals would be too disclosive, the main value would lay in contextualising them through comparison to a wider population. Overcoming the barriers to accessing contextualising data for analysis can minimise the occurrence where the results of small datasets are not applicable more broadly due to an absence of context or baselines. Although it is likely that small-scale studies will continue to be the primary route through which energy studies are performed, putting in place stronger protocols and methods for data access, linking and anonymising will help to ensure their value in addressing broader population-level challenges.

Energy demand and buildings research is hampered by a lack of good quality data either because it does not exist or it is difficult to access. The recently established Research Council UK (RCUK) Centre for Energy Epidemiology Data Service (CEEDS) aims to address both issues by promoting the generation of new, high-quality datasets (e.g. a UK longitudinal energy demand in housing survey) and promoting sharing of existing datasets. However, doing so requires addressing a number of barriers to data sharing that relate to individuals, researchers and organisations, a selection of which are:

- Data Privacy – there is a growing debate surrounding the real or perceived data privacy concerns of individuals including concerns relating to security and criminal activity (e.g. fears about criminal misuse of smart meter data). The UK Data Protection Act, for example, additionally places legal obligations on organisations handling personal data that can hamper data sharing.
- Commercial Sensitivities – data is now regarded as having a commercial value that an organisation may want to exploit directly (by selling data) or by generating insight to gain commercial advantage. There is corresponding fear of being put at commercial disadvantage if data is exploited by competitors;
- Academic Intellectual Property – in a similar fashion, academic researchers may fear losing a valuable resource which might be an integral part of future research;
- Reputational – fear of data errors being discovered or analysis/results being questioned;
- Lack of resources to prepare data for sharing;
- A lack of perceived reward for sharing data

5. Mechanisms to support access

To overcome these challenges, issues and perceptions around commercial sensitivity and privacy must be addressed through the development and implementation of processes that provide assurances to data providers (and their subjects) that their data will be securely stored and privacy maintained. Whilst this will mean putting in place the necessary data infrastructure to allow for data to be stored and managed safely and maintained, addressing these concerns will also require improving the data literacy of researchers, data donors, data creators and collectors, so that data is taken more seriously within the field of energy and buildings researcher. Making the case for why data should be stored and linked goes beyond outlining the benefits for researchers but should clearly outline the wider social and commercial benefits so that support can be built up. In health sciences, linking data together is often argued as a public good to address urgent health problems or events, which means ethically weighing the concerns for person privacy versus the wider social good. Ethics boards made up of government, academic and industry experts are tasked with reviewing the merits of data access and linking proposals and have an obligation to judge whether an individual's data can be used outside of its original collection purpose [20]. The energy and buildings research field does not have the same legal or governance background as health research but there is growing demand for making data that is perceived as private, such as smart meters or in-home temperature, accessible for research and technology development. The UK, for example, is setting out the legal framework for the licensing and management requirements of storing and accessing 'smart-meter' energy data for researchers and developers [21].

A number of mechanisms can be put in place to help address the barriers of sharing data and realising the potential benefits of making high-quality, well structured data accessible to a wider community of energy and buildings researchers and practitioners. These include:

- Funder requirements – research councils and industry funders should put in place requirements for data to be collected and stored in accessible repositories as part of any publicly funded energy and buildings research (as has happened in other science domains).
- Available funds – research councils need to make funds available for data management, storage and making accessible. They should also required that funds are sought in research proposals that will enable this.
- Government support and regulation – Government ministries need to seriously address how they manage administrative data and make it available to researchers and industry. Regulations need to be put in place that allow for appropriate access whilst ensuring privacy is maintained without being draconian in nature.
- Industry interest – Industry must take a leading advocacy role in pressuring public funding bodies to require that data on energy demand and buildings is made more accessible (under appropriate conditions).
- Journal requirements – Journals can require that any datasets used in published research are logged with a recognised repository (with appropriate embargo periods if necessary) and that meta-data is published alongside study results.

6. Conclusions

The transition towards a sustainable built environment and the step-change increase in efficiency and reduction in energy demand will be facilitated by the unprecedented availability of and access to new energy and buildings data. For example, through the installation of high frequency metering and sensors, a huge amount of information can be accessed to describe patterns of demand, manage peak loads, and allow consumers to interact with the supply system and be charged an accurate and fair price. In the near future, minute-to-minute data from high-frequency meters could become more widely available. This data will need to be subject to high levels of protection for privacy; however, with the development of suitable controls and under the aegis of the government, access to anonymised data could be extended across the research community to create an unprecedented, open environment for empirical testing of theory, policy and technology. The buildings and energy demand field must build on the lessons learnt around data access and protection in the health research field. Just as linking patient records to the use of health services has led to the development of epidemiology as an indispensable part of public health policy, the availability and use of individual and sub-meter high frequency data and collection of building and occupant data through robust research designs can support an epidemiological approach, essential for the development of policy for evidence-based energy demand.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) 'New Empirically- Based Models of Energy Use in the Building Stock' under EP/I038810/1; and EPSRC 'Research Councils UK (RCUK) Centre for Energy Epidemiology' under EP/ K011839/1.

References

[1] Summerfield AJ, Lowe RJ. Challenges and future directions for energy and buildings research. Build Res Inf 2012;40:391–400. doi:10.1080/09613218.2012.693839.

[2] Skea J. Research and evidence needs for decarbonisation in the built environment: a UK case study. Build Res Inf 2012;40:432–45. doi:10.1080/09613218.2012.670395.

[3] Lowe RJ, Oreszczyn T. Regulatory standards and barriers to improved performance for housing. Energy Policy 2008;36:4475–81. doi:10.1016/j.enpol.2008.09.024.

[4] Lomas KJ. Decarbonizing national housing stocks: strategies, barriers and measurement. Build Res Inf 2009;37:187–91.

[5] Oreszczyn T, Lowe RJ. Challenges for energy and buildings research: objectives, methods and funding mechanisms. Build Res Inf 2010;38:107–22. doi:10.1080/09613210903265432.

[6] Lomas KJ. Carbon reduction in existing buildings: a transdisciplinary approach. Build Res Inf 2010;38:1. doi:10.1080/09613210903350937.

[7] Whitesides GM, Crabtree GW. Don't forget long-term fundamental research in energy. Science (80-) 2007;315:796–8. doi:10.1126/science.1140362.

[8] Boyd D, Crawford K. Critical Questions for Big Data. Information, Commun Soc 2012;15:662–79. doi:10.1080/1369118X.2012.678878.

[9] Piwowar HA, Becich MJ, Bilofsky H, Crowley RS. Towards a data sharing culture: recommendations for leadership from academic health centers. PLoS Med 2008;5:e183. doi:10.1371/journal.pmed.0050183.

[10] Kaye J, Heeney C, Hawkins N, de Vries J, Boddington P. Data sharing in genomics--re-shaping scientific practice. Nat Rev Genet 2009;10:331–5. doi:10.1038/nrg2573.

[11] Liddiard R. Room scale profiles of space use and electricity consumption in non-domestic buildings. Build Res Inf 2013.

[12] Steadman P, Hamilton I, Evans S. Energy and urban built form : an empirical and statistical approach 2013.

[13] Piwowar HA, Day RS, Fridsma DB. Sharing detailed research data is associated with increased citation rate. PLoS One 2007;2:e308. doi:10.1371/journal.pone.0000308.

[14] DECC. Process Evaluation of the Warm Front Scheme. 2014.

[15] Hamilton IG, Shipworth D, Summerfield AJ, Steadman P, Oreszczyn T, Lowe R. Uptake of energy efficiency interventions in English dwellings. Build Res Inf 2014;42:255–75. doi:10.1080/09613218.2014.867643.

[16] Huebner GM, McMichael M, Shipworth D, Shipworth M, Durand-Daubin M, Summerfield AJ. The shape of warmth: temperature profiles in living rooms. Build Res Inf 2014:1–12. doi:10.1080/09613218.2014.922339.

[17] Kelly J. Disaggregating Smart Meter Readings using Device Signatures. Imperial College London, 2011.

[18] Laurent M, Allibe B, Tigchelaar C, Oreszczyn T, Hamilton I. Back to reality : How domestic energy efficiency policies in four European countries can be improved by using empirical data instead of normative calculation. ECEEE Summer Study Energy Effic First - Found a Low-Carbon Soc 2013;7:2057–70.

[19] Borgman CL. The conundrum of sharing research data. J Am Soc Inf Sci Technol 2012;63:1059–78. doi:10.1002/asi.22634.

[20] UK Parliament. National Health Service Act 2006 2006.

[21] DECC. Smart Metering Implementation Programme Smart Energy Code: Consultation. London, UK: Department of Energy and Climate Change; 2012.